THE SIGNIFICANCE OF WAVE-FORM FOR OUR COMPREHENSION OF AUDITION.

By MAX MEYER.

A recent number of the *Zeitschrift für Psychologie*[1] contains a set of curves representing the resultants of two sinusoids each for all the ratios made up of the numbers from 1 to 12. It contains, further, the resultant curves of the ratio 2:3 for various phase-differences, and the resultant curves for the ratios 4:5:6, 4:5:9, and 4:7:9. In the accompanying article, Professor C. Stumpf discusses these curves with an aim indicated by the following remarks. There is no doubt that the Helmholtzian theory of audition in its traditional form is imperfect. In order to modify it, we ought to study the characteristic properties of the various forms of compound curves. Then only can modifications of the theory be worked out. Even those who believe in the theory of resonance quite literally, will be able to obtain from a study of such curves material for the criticism of theories which are not based on the assumption of resonators in the ear.

The present writer took a special interest in this paper, because many years ago he studied the same curves with the same aim. He was soon led, however, to a point of view different from that of Professor Stumpf.

In the first place, there arises the general question: What is the use of *mathematical* speculations about wave forms? They will never be of any use whatsoever, unless they can lead to some idea about the *mechanical* processes taking place in the organ of hearing, in the cochlea. Now, to obtain such an idea we have to search in a region where there are no previously established paths. The only aids for findiug our way in this darkness are the following observations:

1. Auditory stimuli, according to a general agreement, consist of *oscillations.* But nothing compels us to assume *apriori* that oscillations must be of the form of sinusoids in order to stimulate the auditory organ. *They might be of other forms.*

2. When we look at a compound curve, *i. e.*, a curve made up by the geometrical addition of, say, two sinusoids, *it looks* to us

[1] Zeitschrift f. Psy. u. Physiol. d. Sinn. XXXIX, p. 241-268.

like a sum of several oscillations (of whatever *form* they may be), just as *we hear* a sum of several tones. By comparing various ways of *looking at curves* with the tones we actually *hear*, we might discover that some ways of looking lead to a greater resemblance than others between what we see and what we hear.

3. Having found a way of looking at curves which leads to a considerable resemblance between what we see and what we hear, we should try to find out whether our organ of hearing could *function mechanically* in the manner indicated by our way of looking at the curves. If we discover such a function, then our problem is practically solved.

Upon the general principles just stated there seems to be agreement between Professor Stumpf and the writer. There is no agreement, however, upon the special paths by which to proceed in the application of these principles.

1. *What is an oscillation?*

Professor Stumpf and the writer agree that a definition of "an oscillation" must be altogether a matter of utility. But the writer cannot accept the use of the "middle line" for a definition. On the contrary, he has long believed that this use narrows down the possibilities of looking at curves to such an extent that we can never hope, by its means, to reach a satisfactory agreement between what we see and what we hear.

By "middle line," Professor Stumpf means the horizontal co-ordinate when so placed that all the points of inflection of the original sinusoids come to lie on it. And by "an oscillation" he means (p. 244) a part of the compound curve which starts from a point on the "middle line," returns to the "middle line," passes over to the other side of this line, and returns a second time to a point upon it. The part of the curve from the starting point to the second crossing of the middle line is "one oscillation." He emphasizes the fact that it is our purpose in a study of such curves to *count the oscillations*, thus or so defined. But he does not say how we should define and count oscillations in case the curve moves towards the middle line and then away from it *without touching it*. This course occurs in innumerable instances, when the amplitudes of the original sinusoids are unequal. In such a case, we could not simply omit the up-and-down movement in question, or we should get a collection of tones which in reality no one hears. The writer is, naturally, very far from asserting that a definition of an oscillation is altogether valueless, because it is applicable only to the special case of equal amplitudes; but he believes that, when all the facts are considered, Professor Stumpf's definition by means of the middle line must be pronounced inferior to that which he himself published in the

Zeitschrift, Vol. XI, p. 216-217 (1896). In the writer's definition, Professor Stumpf's "middle line" plays no part. The question, therefore, need not be raised whether a maximum or minimum reaches beyond or touches the "middle line," or fails to do so. What is of primary importance, in the writer's definition, is the *ordinate differences* of the maxima and minima, not the ordinate values themselves. The absolute ordinate value of a single maximum or minimum (referred to in Professor Stumpf's "reaching beyond," "touching," or "leaving untouched" the "middle line") should not enter into a definition, because the location of the horizontal co-ordinate is arbitrary and, therefore, cannot possess any mechanical significance.

This, perhaps, is the chief difference between the writer's attitude toward the present problem and the attitude of Professor Stumpf: that the former insists always upon the possible mechanical significance of the oscillations. In the publication above mentioned, the writer showed (p. 225) the possibility of such a mechanical significance, although he did not then succeed in making this particular mechanical application appear very probable from an anatomical point of view. Professor Stumpf, however, is apparently satisfied with definitions of oscillations as such. He leaves the mechanical side of the problem to the future. He seems to imply (p. 255, line 6, "Endlich") that there is to be found here a collection of *all possible* definitions of "oscillations," so that the future investigator must choose among the five given. But in reality, the number of such definitions, since they are, naturally, not logical deductions from a single principle but arbitrary inventions for purposes of utility, might be largely increased. In particular, the definition of "an oscillation" developed by the present writer is not mentioned. Now, since *all* such definitions of "oscillations" are originally equally arbitrary, it would appear that those and those only should be selected for discussion which evince a certain amount of harmony with the facts of auditory observation and which can be shown to possess a certain mechanical significance. The remarks by Professor Stumpf on pp. 266-268 do not seem to the writer a fulfilment of these two conditions.

The definition of "oscillation" just spoken of is mentioned by Professor Stumpf on p. 254 under (2). He mentions under (1) another definition, which regards the whole period of the sum of the two sinusoids as a single oscillation, but discards it as inadequate. Let us, then, turn to the three remaining definitions. The third, which again makes use of the "middle line," is this: "An oscillation is the double length of the first section of the middle line in case $\frac{H}{L} \leqq 3$, the double length

of the sum of the first two sections of the middle line in case $\frac{H}{L} > 3$. The frequency of oscillation is then $\frac{H+L}{2}$."

The fourth definition is this: An oscillation is the period from one relatively highest (*i. e.*, having lower ones at either side) maximum to the next relatively highest maximum of the curve. The frequency of oscillation is then equal to H—L in case $\frac{H}{L} \leqq 2$, equal to L in case $\frac{H}{L} > 2$.

The fifth definition is this: An oscillation is generally identical with the component sinusoid of lowest frequency. The frequency of oscillation is then simply L.

II. *What definition is the most promising?*

It is clear that all definitions of "an oscillation" have for their immediate purpose the finding of an agreement between the result of our "looking" (perhaps it would be better to say "counting oscillations by looking") at curves and our auditory experiences. The agreements found here are the following:

Looking at the "middle line," in accordance with the second definition, may "explain" to us why we can hear the *higher* one of the two original tones. (*H.*)

Looking at the "middle line," in accordance with the third definition, rather contradicts than agrees with observation; for we do not universally hear a *mean tone* $\frac{H+L}{2}$. We hear such a tone only with very special and rather rare ratios (very small intervals). (*M.*)

Looking at a curve in accordance with the fourth definition may "explain" *one difference-tone* in cases where the interval is less than an octave. It does not indicate the fact that we can often, indeed usually, hear more than a single difference-tone. As regards difference-tones of larger intervals, the definition reveals only the negative fact that the tone H—L is there not ordinarily audible, but nothing positive; although in fact certain difference-tones are nearly always clearly audible in such intervals. (*D.*)

Looking at a curve in accordance with the fifth definition may "explain" why we can hear the *lower* one of the two original tones. (*L.*)

It is plain, then, that for the sake of an "explanation" of the most ordinary phenomena of audition (1. hearing *H*, 2. hearing *L*, 3. hearing *one D*), we should have to apply to a given curve at least *three different definitions of "an oscillation" at the same time;* if we wished to include the "mean tone," *even*

four different definitions at the same time! It is not likely that anything of scientific value will be gained in this manner.

For comparison, the writer's *single* definition of "an oscillation" is translated here from *Zeitschrift* XI, p. 216: "Find the smallest ordinate difference between a maximum and the preceding minimum (or the reverse; the order is irrelevant), and cut off from each ridge and each trough of the wave a piece whose height is equal to one-half of this difference. Each pair of a higher and a directly following lower segment of this kind counts as "one oscillation." The height of the segments is to be regarded as a measure of the intensity of the tone. Apply the same rule to the wave remaining, and so on until the wave is reduced to a straight line."

This *single* definition of an oscillation "explains" more than all the present five together; it explains, *e. g.*, the fact that we can hear several difference-tones at the same time. Of course, one must not expect the definition to explain every detail of audition; that is, in any case, no serious matter. A definition of this kind is not an end in itself, but merely a means to an end; the end being the discovery of the mechanical function of the inner ear. This leads us to the third point of our discussion.

III. *The mechanical significance of the writer's "oscillation."*

How does the inner ear function mechanically? All studies of curves and wave-forms, all definitions of oscillations and their relations to the facts of audition, are mere means, tools, aids in the approaching of this problem. And therefore, any definition of "oscillation," any manner of looking at compound curves, is scientifically valuable only in so far as it suggests a definite mechanical process which must be found possible under the anatomical conditions of the cochlea. Now Professor Stumpf's paper gives no suggestion of a mechanical process corresponding to any one of his definitions of "oscillations." On the other hand, having found the definition above mentioned, the writer attempted to find a mechanical process which was in accord with it. Such a process is described in *Zeitschrift* XI, p. 225, directly following the definition of "oscillation." The mechanical process, however, which he was at that time able to discover, although unobjectionable from a purely physical point of view, offered a considerable anatomical difficulty. It assumed an imperfectly elastic rod, fastened to a support at the one end, the free end moving transversely in the form of the compound curve. But what anatomical structure could be a rod of such properties? This was the unsatisfactory part of the assumption.

However, a few months after this publication, the writer hit upon an idea which led to the unfolding of what he now re-

gards as the correct—though incomplete—theory of the mechanical function of the inner ear. The anatomical difficulty was solved. This solution is published in outline in *Zeitschrift* XVI, p. 22. He found that the following mechanical process would correspond exactly to his definition of "oscillation." Imagine a relatively long and narrow tube, divided lengthwise, by a flexible but perfectly inelastic band or partition, into two tubes of approximately semi-circular cross-section. The partition, being inelastic, could not, when displaced, return to its normal position by its own force, but only under the influence of external forces. Imagine this partition to be restricted in its movement, so that in either direction it can yield to pressure only within narrow limits. Imagine, further, this tube to possess at the one end two windows closed by membranes, one window for each division of the tube. Imagine a piston-like body to be attached to the membrane of one of the windows. Now, when this piston-like body moves back and forth in the form of any given compound curve, we shall observe on the successive sections of the partition "oscillations" which are exactly like those above defined. Details of this view or "theory" may be found in the paper mentioned and in other publications of the writer's. Here a few further explanations may be added. Under the conditions assumed, the length of the section of the partition which—point after point—yields to the movement of the piston must always be proportional to the distance through which the piston moves in one and the same direction. And whenever the piston reverses its movement, *begins* to move in either direction, the point of the partition which first yields must be that nearest the windows; the other points yield later. This last principle may be exemplified by the fact that a gun barrel sometimes explodes although the front end is open; in the same way the initial sections of the partition yield before those more distant.

The anatomical application of this mechanical function is at once clear. The cochlea is a relatively long and narrow tube. It is divided by a flexible partition into two divisions. Each division has a window at the one end of the tube. And one of these windows contains a piston-like body, the stirrup.

But there is one seeming difficulty left. The partition in the cochlea, although undoubtedly flexible, *cannot be regarded as perfectly inelastic.* But this, far from being a serious difficulty, explains what otherwise would be another difficulty. The partition is certainly not perfectly inelastic; and it must be its very elasticity which confines its yielding movements within the limits above spoken of. Not, of course, that by assuming a certain degree of elasticity of the partition we relapse into the resonance theory, the piano-in-the-ear doctrine :

we assume some elasticity, but *no tension*. Indeed, it is not easy to see how tissues which are under *constant* tension during the whole life of the individual could retain their tension, and not simply grow longer, adapt themselves, and thus lose their tension. This is what happens wherever constant tension is observed in growing, living tissues, vegetable or animal.

The task now left is to work out the mechanics of the inner ear in detail, making use of all the anatomical facts at our disposal. The writer has worked out, to some extent, a very few of these details, and has published the results in various papers. However, we still have only the barest outlines of a mechanics of the inner ear.

It has been mentioned that the writer's definition of "an oscillation" does not agree in every detail with the facts of audition. It has now become clear why there could not be a perfect agreement: the mechanical theory which is strictly equivalent to that definition is—from the anatomical point of view—*only a close analogue of the mechanics of the inner ear*, not its true representative.

The progress of the mechanical theory, if such progress should result from an increased interest in this matter among scientists, is sure to have a beneficial influence on our purely psychological knowledge of the facts of audition. Whoever has attempted to familiarize himself, *e. g.*, with the results of such otherwise admirable work as that of Krüger on difference-tones, must have been convinced of the enormous waste of mental energy resulting from the fact that these experiments were scarcely made with definite questions in view. Experiments which are not made on the basis of a definite theory may nevertheless lead to valuable discoveries; but they are more apt to lead to the collection of a mass of material so large that no one can mentally digest it. With the progress of the theory, there will also come a new advance in experimentation.